AFRL-OSR-VA-TR-2014-0177

High-Power Microwave Metamaterials for Phased-Array

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07/23/2014
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12-07-2014

2. REPORT TYPE
Final Performance Report

3. DATES COVERED *(From - To)*
15-4-2011-14-4-2014

4. TITLE AND SUBTITLE
High-Power Microwave Metamaterials for Phased-Array, anti-HPM, and Pulse-Shaping Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-11-1-0050

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nader Behdad

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
THE BOARD OF REGENTS OF THE UNIVERSITY OF WISCONSIN
RESEARCH &SPONSORED PROGRAMS
21 N. PARK STREET SUITE 6401
MADISON, WI 53715-1218

8. PERFORMING ORGANIZATION REPORT NUMBER
144-PRJ47CT-Final

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This document is the final performance report of the Young Investigator Program (YIP) project funded by the Air Force Office of Scientific Research. The report discusses the tasks performed during the entire three year duration of the project and the outcomes achieved.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Nader Behdad
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	18	19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified			(608) 262 8804

FINAL PERFORMANCE REPORT

Contract/Grant Title: High-Power Microwave Metamaterials for Phased-Array, anti-HPM, and Pulse-Shaping Applications.

Contract/Grant No.: FA9550-11-1-0050

Reporting Period: 15 April 2011 – 14 April 2014

Report Date: 12 July 2014

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Contents

1. Abstract

Final performance report of the Young Investigator Program (YIP) project titled "High-Power Microwave Metamaterials for Phased-Array, anti-HPM, and Pulse-Shaping Applications" is presented in this document. The research conducted in this project resulted in a number of unique devices for operation in high-power microwave systems. Specifically, for the very first time, high-power frequency selective surfaces capable of handling extremely high-power levels were introduced and experimentally demonstrated. Other major findings of this project include the introduction, development, and experimental demonstration of two new classes of ultra-wideband, true-time-delay, and high-power-cable microwave lenses suitable for operation in high-power phased-array antennas and electronic attack systems. Through the basic research conducted in this project, a better understanding of breakdown and plasma generation in high-power microwave periodic structures and metamaterials was achieved. This new understanding resulted in the development of new techniques for creating fast acting, distributed discharge limiters as well as periodic plasma layers. Finally, the use of metamaterials in high-power microwave amplifiers was investigated and a new concept for designing high-power, millimeter-wave traveling wave tubes was introduced and verified using computer-based simulations.

2. Summary of Main Accomplishments of This Project

The broad objective of this project was to investigate artificially engineered materials (metamaterials) capable of operating under extremely high power microwave (HPM) fields. We first investigated the use of wideband, high-power-microwave metamaterials composed of non-resonant unit cells in the design of HPM frequency selective surfaces and spatial phase shifters (SPSs). The results of our investigations in this area are provided in Section 3. Subsequently, we investigated various mechanisms for dynamically tuning the responses of such metamaterial structures. These include electronic, micro-fluidic, and optical tuning techniques. The results of our investigations in this area are provided in Section 4 of this document. Using the sub-wavelength periodic structures developed in this work, we developed several new types of microwave lenses and investigated their applications in high-gain, high-power antenna systems as described in Section 5 of this document. As part of this project, we also investigated the physics of breakdown processes in high-power metamaterials and periodic structures. In Section 6 of this document, we outline our findings in this area. These findings are expected to facilitate the design of plasma-tunable structures, rapid distributed discharge limiters, and devices that generate periodic plasma over very large scales. Finally, in Section 7 of this report, we describe our research in the design of a new class of metamaterial-enhanced traveling wave tube amplifiers.

3. High-Power Microwave Frequency Selective Surfaces and Metamaterials

3.1. Theoretical Investigation of Electromagnetic Wave Tunneling Through Epsilon- and Mu-Negative Slabs.

One of the main objectives of this project was to examine the application of a class of metamaterials composed of nonresonant periodic structures in the design of high-power-microwave (HPM) frequency selective surfaces (FSSs) and metamaterials. We started our investigations in this area by examining the problem of electromagnetic wave tunneling through a stacked arrangement of double-positive (DPS) dielectric slabs and epsilon-negative (ENG) layers as shown in Fig. 1. The ENG slabs are essentially layers of dense plasma that are operated at a frequency below their plasma frequencies. We demonstrated theoretically that electromagnetic waves can tunnel through such stacked layers even at frequencies where each plasma layer is individually opaque. Furthermore, we demonstrated that this problem can be converted to a classical microwave filter design problem and provided an alternative explanation for how EM waves can tunnel through such structures. Through this analogy, we developed a synthesis procedure for synthesizing such multi-layer structures to provide a given desired frequency response. The results of this theoretical investigation were published in the Journal of Applied Physics in 2012 [J1]. We also examined the phenomenon of EM wave tunneling through a stacked layer of mu-negative (MNG) metamaterial layers separated from one another by DPS layers (i.e., the dual of the structure shown in Fig. 1). The results of this investigation were published in an article in Progress of Electromagntics Research [J2].

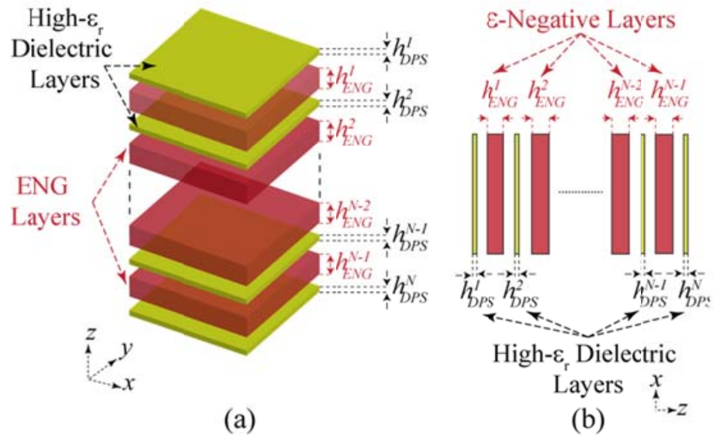

Fig. 1. (a) Three-dimensional view of a number of double positive dielectric layers separated from one another by epsilon-negative metamaterial layers. (b) The side view of the structure.

3.2.Experimental Demonstration of High-Power Microwave Filters

Following our theoretical investigations of the phenomenon of electromagnetic wave tunneling through stacked layers of ENG and DPS metamaterials, we examined the techniques that can be used to practically implement these structures to achieve a high-power-capable microwave filter. Specifically, we examined implementation of the ENG layers using rectangular waveguides operating below their cutoff frequencies. We also investigated the implementation of the ENG layers using wire grid structures with small periodicities and extremely small sub-wavelength holes. We demonstrated that both techniques can be used to emulate the structure shown in Fig. 1 and to obtain filters or frequency selective surfaces that are capable of high-power microwave operation. We also fabricated prototypes of two such filters and demonstrated that they are indeed capable of handling extremely high peak power levels. Specifically, our theoretical investigations demonstrated that such filters are capable of handling peak power densities as high as 1.0 MW/cm^2. We also conducted high-power microwave experiments using the setup shown in Fig. 2. In this setup, a magnetron is used as the high-power microwave source and it is used to generate a short duration pulse with a peak power level of 25kW and a pulse duration of 1μs. The magnetron generates a single frequency pulse with the frequency of 9.382 GHz. Therefore, the HPM filters were designed to have a pass band at this frequency. The device under test is placed inside a rectangular WR-90 waveguide and the incident, reflected, and transmitted pulses are sampled using directional couplers as shown in Fig. 2. Using this setup, the time-domain transmission and reflection coefficients of the DUT can be measured. We experimentally demonstrated that our HPM filters are capable of handling at least 25 kW peak power levels.

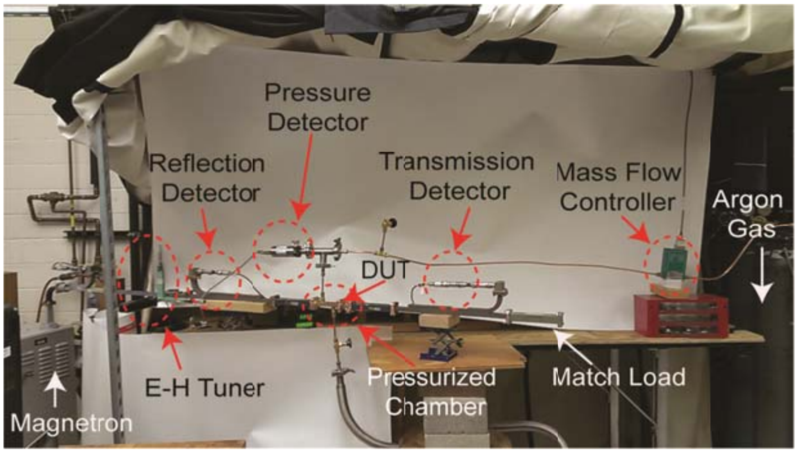

Fig. 2. The photograph of the experimental setup used to measure the time-domain reflection and transmission coefficients of the high-power microwave filters and frequency selective surfaces that are developed in this YIP project.

Although, the true power handling capability of these filters is expected to be significantly higher than this value. However, due to the lack of availability of an HPM source with a higher peak power level, we conducted the experimental studies at the peak power level of 25 kW max. The detailed results of this investigation and the experimental measurement results are published in a journal paper in the Journal of Applied Physics [J3].

3.3. Design and Experimental Demonstration of High-Power Microwave Frequency Selective Surfaces

In this project, we also examined the peak power handling capability of a class of miniaturized-element frequency selective surfaces (MEFSSs) composed entirely of non-resonant constituting elements. These FSSs are composed of a number of metal layers separated from one another by thin dielectric layers. Each metal layer is in the form of a two-dimensional periodic arrangement of sub-wavelength capacitive patches or a two-dimensional wire grid structure with sub-wavelength periodicity. The effects of various design parameters on the peak power handling capability of these structures were investigated using electromagnetic simulations and methods for increasing their peak power handling capability were proposed. These methods were used to design a high-power microwave (HPM) frequency selective surface (FSS), which is expected to be capable of handling extremely high peak power levels. Specifically, the HPM FSSs developed in this project are expected to be capable of handling peak power densities as high as 1.0 MW/cm^2. Fig. 3 shows the topology of the proposed HPM FSS.

The power handling capabilities of these devices were also experimentally investigated using an HPM source with a frequency of 9.382 GHz, a peak power of 25 kW, and a pulse length of 1μs. Unit cells of various FSSs under investigation were placed in a waveguide and excited with pulses with variable power levels. The time-domain reflection and transmission coefficients of each device were measured at various power levels and the power level at which the device breaks down was determined. The results of these experimental investigations followed the same trend observed in the simulations. Additionally, our experiments demonstrated that the HPM FSSs developed in this work were indeed capable of handling extremely high peak power levels. The detailed experimental and theoretical results of this investigation are published in an article in IEEE Transactions on Antennas and Propagation [J4].

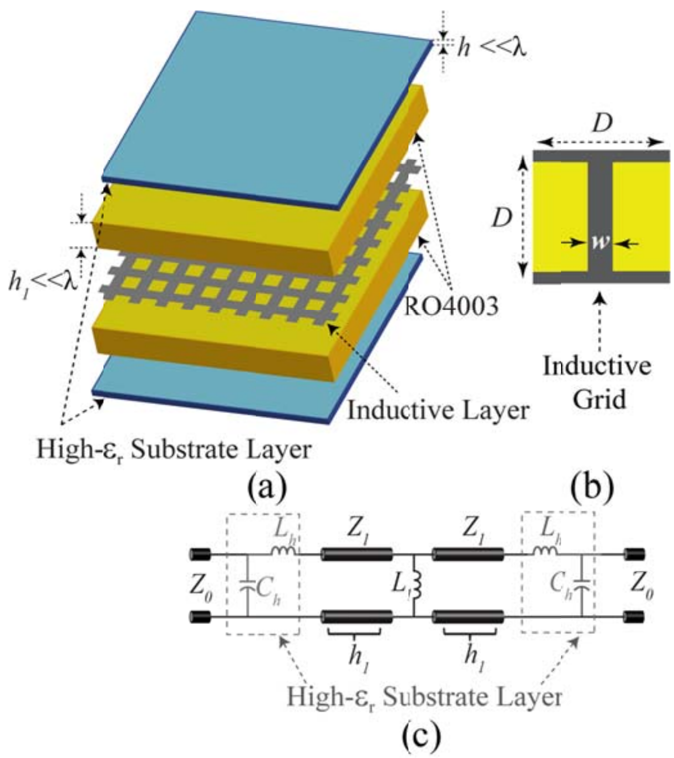

Fig. 3. (a) 3-D topology of a 2nd-order MEFSS using thin high- substrate layers rather than capacitive layers composed of rectangular patches. (b) Top view of one unit cell of the inductive layer. (c) Equivalent circuit model for the 2nd-order MEFSS using thin high- substrate layers.

4. Developing Tuning Techniques for Tuning the Responses of High-Power Microwave Metamaterials

As one of the aims of this project, we examined the techniques that could be used to tune the responses of high-power metamaterials and periodic structures. Specifically, we examined electronic tuning techniques, optical tuning techniques, and fluidic tuning techniques. A summary of our findings in each area is described below.

4.1.Electronic Tuning Techniques

We examined the use of electronic tuning techniques to tune the responses of HPM metamaterials and periodic structures. Specifically we examined the design and analysis of a frequency selective surface (FSS) capable of providing a third-order bandpass response. The transfer function of this FSS was designed to have a transmission null, the frequency of which can be tuned to suppress strong interference signals with frequencies close to or within the main transmission band. We investigated the principles of operation of the device and we developed an approximate analytical procedure for synthesizing the desired FSS response. Two prototypes were fabricated and characterized using a free-space measurement setup and the FSS's different modes of operation were demonstrated experimentally. Finally, the tuning performance of the FSS's transmission null was experimentally demonstrated in a WR-90 waveguide environment. The results of this study were published in a journal paper in IEEE Transactions on Antennas and Propagation [J5].

In the area of electronic tuning technique, we also conducted a number of other studies that focused on investigating the suitability of these techniques for tuning the responses of HPM metamaterials. Specifically, we considered tuning the responses of HPM metamaterials using GaAs and BST based varactors. In both cases, we observed that the nonlinearities of these devices completely disrupt the performance of the metamaterials and periodic structures that use them when operated in high-power microwave conditions. Our findings in this area are published in a sub-section of a journal paper that we published in IEEE Transactions on Antennas and Propagation [J6].

4.2.Optical Tuning Techniques

We also examined the use of optical tuning techniques to tune the responses of HPM metamaterials and periodic structures. The idea behind this concept is rather simple. Specifically, when a photoconductive material is illuminated with light with appropriate wavelength, the conductivity of the material changes. When such photoconductive materials are integrated with unit cells of periodic structures and metamaterials, this change in conductivity can be used to change the properties of the structure. The fact that this tuning method is not an electronic-based technique is particularly useful in high-power microwave applications, since the devices maintain their linearity under HPM operation. However, in our investigations we found out that the range of conductivities that can be achieved using existing photoconductive materials, when the intensity of the incident light is changed, is not wide enough to obtain any meaningful tuning of the responses of the metamaterials under investigation. Specifically, for this proposed scheme to work, a wide tuning range of conductivities as well as very high levels of conductivities were needed. Using existing photoconductive materials and technologies only allows for achieving very limited tuning range and the devices designed using these materials were found to suffer from excessive loss levels. Therefore, we abandoned this approach in favor of liquid tuning technique as is described in Section 4.3. We point out that optical techniques may have a place in designing reconfigurable metamaterials and periodic structures for certain specific applications. For example, we believe that they are particularly useful in converting an FSS to an absorber or to turn on/off a periodic structure. However, since the goal of our current investigation was to develop tunable structures with relatively low loss values, this approach was not pursued any further.

4.3.Fluidic Tuning Techniques

In this area, we examined fluidically tunable periodic structures acting as highly-selective frequency selective surfaces (FSSs) or spatial phase shifters (SPSs) capable of providing phase shifts in the range of $0° - 360°$. These devices were multi-layer periodic structures composed of non-resonant unit cells. The tuning mechanism was based on integrating small, movable liquid metal droplets with the unit cells of the periodic structure. By moving these liquid metal droplets by small distances within the unit cell, the structure's frequency response can be tuned continuously. Fig. 4 shows the three-dimensional topology of one such fluidically-tunable structure.

Using this technique, a fluidically tunable FSS with a fifth-order bandpass response was designed and its tuning performance was examined for various incidence angles and polarizations of the incident EM wave. Additionally, electronically tunable counterparts of the same structure were also designed and their tuning performances were examined under short-duration high-power excitation conditions. It was demonstrated that such electronically tunable FSSs/PSSs demonstrate extremely nonlinear responses. Since the fluidically tunable structure examined in this work does not use any nonlinear devices, its response is expected to remain linear for such short-duration high-power excitation conditions. The tuning performances of

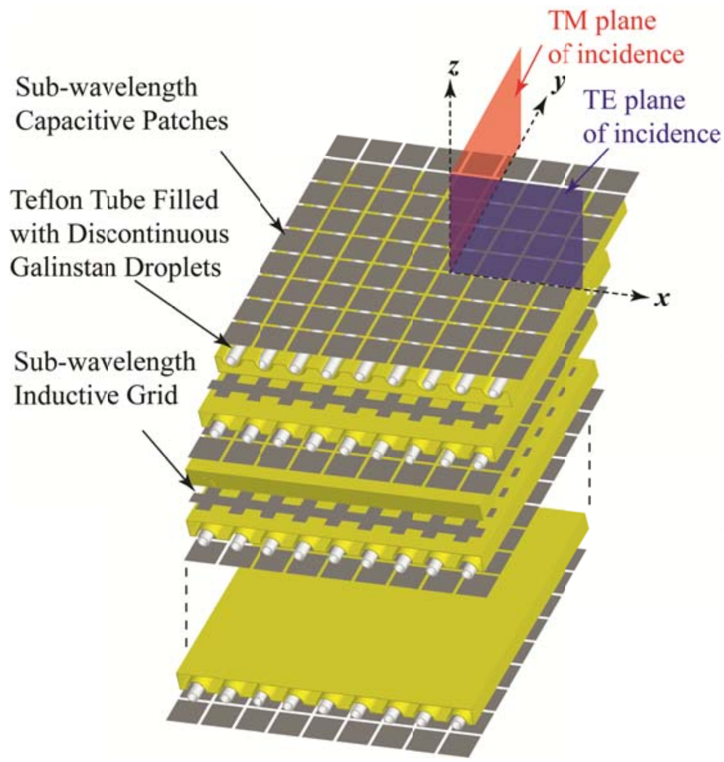

Fig. 4. Topology of a fluidically tunable iniaturized-element frequency selective surface. The structure is composed of successive capacitive and inductive layers separated from one another by thin dielectric substrates. Columns of Teflon tubes, containing discontinuous Galinstan droplets, are embedded within the dielectric substrates to dynamically tune the surface impedances of the capacitive layers.

these fluidically tunable periodic structures are also experimentally demonstrated by fabricating three prototypes and characterizing their responses in a waveguide environment. The results of this investigation are published in a lengthy journal paper in IEEE Transactions on Antennas and Propagation [J6].

5. Broadband and True-Time-Delay Microwave Lenses for High-Gain, High-Power Microwave Applications

5.1. Wideband, Planar Microwave Lenses Using Sub-Wavelength Spatial Phase Shifters

In this area, we developed a new technique for designing low-profile planar microwave lenses. The developed lenses consist of numerous miniature spatial phase shifters distributed over a planar surface. The topology of each spatial phase shifter (SPS) is based on the design of a class of bandpass frequency selective surfaces composed entirely of sub-wavelength, non-resonant periodic structures. We also developed a procedure for designing the proposed lenses and their constituting spatial phase shifters. This design procedure was applied to two different planar lenses operating at X-band. Each lens was a low-profile structure with an overall thickness of $0.08\lambda_0$ and uses sub-wavelength SPSs with dimensions of $0.2\lambda_0 \times 0.2\lambda_0$ where λ_0 is the free-space wavelength at 10 GHz. These prototypes were fabricated and experimentally characterized using a free-space measurement system. The fabricated prototypes demonstrated relatively wide bandwidths of approximately 20%. Furthermore, the lenses demonstrated stable responses when illuminated under oblique angles of incidence. This feature is of practical importance if these lenses are to be used in beam-scanning antenna applications. The results of this study were published in a journal paper in IEEE Transactions on Antennas and Propagation [J7]. Additionally, we examined the utility of this technique in designing lenses with reverse chromatic aberrations. These results are published in a journal paper in Optics Express [J8] in 2012.

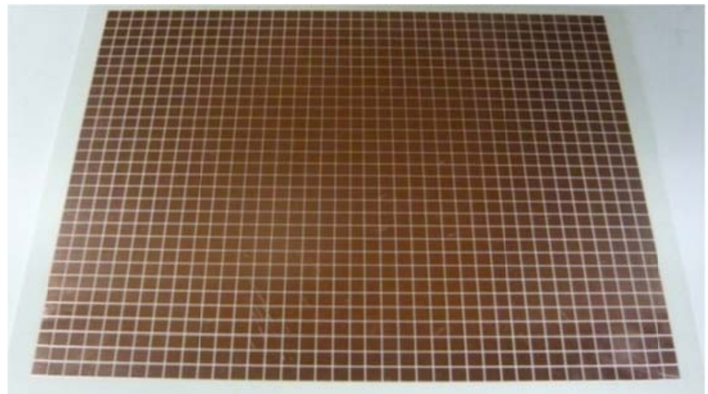

Fig. 5. Photograph of one of the fabricated lens prototypes that use miniature, spatial phase shifters developed in this project. The results are published in [J7].

5.2. Broadband, True-Time-Delay Microwave Lenses Based on Miniaturized Element Frequency Selective Surfaces

We also developed a new technique for designing low-profile, ultra-wideband, true-time-delay (TTD) equivalent microwave lenses. Such a lens is composed of numerous spatial time-delay units (TDUs) distributed over a planar surface. Each spatial TDU is the unit cell of an appropriately designed miniaturized-element frequency selective surface and provides a frequency-independent time delay within the frequency band of interest. Two TTD lens prototypes with focal length to aperture dimension ratios of 1 and 1.6 were designed, fabricated, and experimentally characterized at X-band. The 3-dB gain bandwidths of these lenses were measured to be respectively 7.5–11.6 and 7.8–11.5 GHz. Fig. 6(a) and Fig. 6(b) show photographs of the two fabricated lens prototypes developed in this part of project. Each fabricated lens has an overall thickness of 4.76 mm, which corresponds to $0.15\lambda_0$, where λ_0 is the free-space wavelength at the center frequency of operation. Each lens uses spatial TDUs with physical dimensions of $6 \times 6\ mm^2$, or $0.19\lambda_0 \times 0.19\lambda_0$. Both lenses have a system fidelity factor close to 1, when excited with a broadband pulse. Furthermore, due to their true-time-delay equivalent behavior, the fabricated lenses do not suffer from chromatic aberration within their operational bands. When used in a beam-scanning antenna system, each lens demonstrates an excellent scanning performance in a field of view of $\pm 60°$. The results of this study are published in a journal paper in IEEE Transactions on Antennas and Propagation [J9].

5.3. Wideband, True-Time-Delay Microwave Lenses Based on Metallo-Dielectric and All-Dielectric Lowpass Frequency Selective Surfaces

In addition to our work described in Section 5.2, we developed another new technique for designing microwave lenses with broadband, true-time-delay response types. The lenses developed in this work are planar structures with circular apertures populated with numerous spatial time-delay units (TDUs). Each TDU is the unit cell of an appropriately designed lowpass frequency selective surface (FSS) that provides a desired time delay over a wide frequency range. The lowpass FSSs used in this work are either metallo-dielectric or all-dielectric type multi-layer structures. A metallo-dielectric lowpass FSS is composed of a number of capacitive patch layers separated from each other by thin dielectric substrates. An all-dielectric lowpass FSS, on the other hand, is composed of high- and low- dielectric substrates cascaded sequentially. Two metallo-dielectric lowpass FSS-based true-time-delay (TTD) lens prototypes and one all-dielectric lowpass FSS-based TTD lens prototype with focal length to aperture diameter ratios of 1, 1.5 and 1.3 were designed, fabricated, and experimentally characterized. They respectively operate over a bandwidth of 30%, 50% and 40% without any chromatic aberrations. This was demonstrated experimentally by characterizing the responses of these

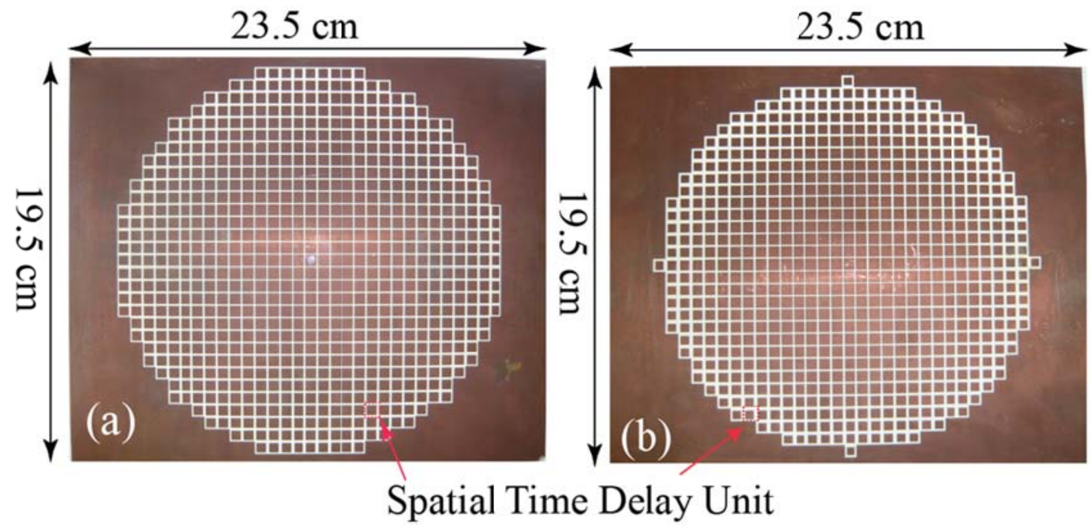

Fig. 6. (a) Photograph of the fabricated lens prototype with 12 zones and a . (b) Photograph of the fabricated lens prototype with 16 zones and an . In both of these figures, the only visible metallic layer is the first capacitive layer within which the size of the capacitive patches decrease from the center of the lens to the edges. Note here the same trend exists for all the other capacitive layers located in the interior layers of the structure.

lenses both in frequency domain and in time domain. Moreover, all of these lenses demonstrated excellent scanning performances with fields of views of $\pm 60°$ within their entire frequency bands of operation. Fig. 7 shows the photograph of the fabricated all-dielectric lens prototype.

The microwave lenses developed in this work have several advantages over the ones developed in Section 5.2. Specifically, these lenses offer a higher bandwidth particularly at lower frequencies of operation. Additionally, the design of these lenses is simpler than those which use bandpass MEFSSs. Finally, the all-dielectric lenses developed in this work are especially useful for HPM applications as they do not use any metallic elements and the field enhancement factors within their various layers are very small. The results of our investigation in this area were published in a journal paper in IEEE Transactions on Antennas and Propagation [J10], which received the prestigious R. W. P King Award of the IEEE Antennas and Propagation Society in July 2014.

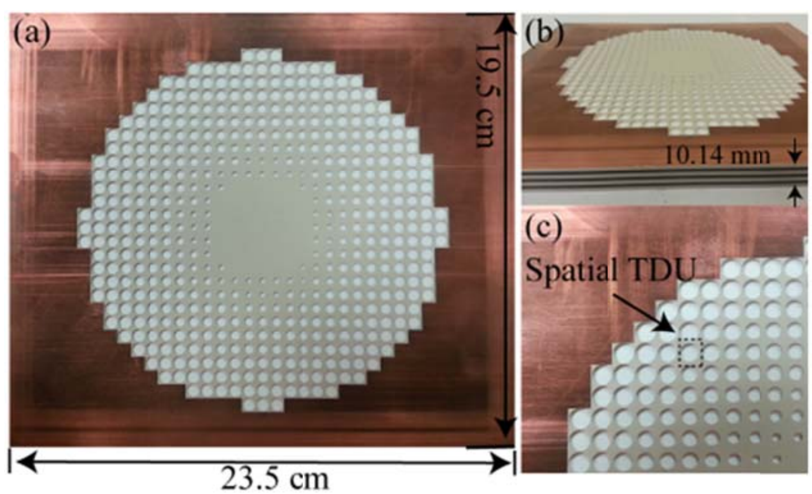

Fig. 7. (a) Top view of the fabricated all-dielectric TTD lens prototype with 12 zones and *f/D=1.3.* (b) Side view of the all-dielectric TTD lens prototype with 12 zones and *f/D=1.3.* (c) The detailed zoom in view of one corner of the only visible high- layer. The size of the substrate through-hole increase from the center of the lens to the edges. Note here the same trend exists for all the other high- layers located in the interior layers of the structure.

5.4. Design of Wideband, FSS-Based Multi-Beam Antennas Using the Effective Medium Approach

As part of this project, we also developed a broadband, low-profile, multi-beam antenna. The antenna uses multiple feed elements placed on the focal plane of a planar microwave lens to achieve high-gain, multi-beam operation with a wide field of view. The lens is based on the metallo-dielectric lenses developed in this project and reported in Section 5.3 and it uses the constituting unit cells of appropriately designed miniaturized-element frequency selective surfaces (MEFSSs) as its spatial time-delay units. A new technique for modeling such lenses was also developed. This new technique simplifies the full-wave electromagnetic simulation of MEFSS-based lenses to a great extent. This technique is based on treating the pixels of the lens as effective media with the same effective permittivity and permeability and significantly reduces the difficulty of modeling and optimizing the proposed multi-beam antenna with its relatively large aperture size in a full-wave electromagnetic simulation tool. Using this procedure, a prototype multi-beam antenna operating in the 8-10 GHz range was designed. The prototype was fabricated and characterized using a multi-probe, spherical near field system. The measurement results were found to be in good agreement with the simulation results obtained using the proposed simplified modeling technique. Measurements demonstrated completely consistent radiation characteristics over the antenna's entire operational band with multiple beams in a field of view of $\pm 45°$ within the entire band of operation of the antenna. The results of this investigation are submitted in the form of a journal paper for evaluation and publication in IEEE Transactions on Antennas and Propagation [J12]. This work is also reported in a number of conference papers [C4], [C11].

5.5. Ultra-Wideband, True-Time-Delay Reflectarray Antennas Using Ground-Plane-Backed Miniaturized-Element Frequency Selective Surfaces

As part of this project, we invented a new method for designing low-profile reflectarray antennas with broadband, true-time-delay (TTD) responses. The structures developed in this work are composed of numerous reflective spatial time delay units distributed over a planar surface. Each spatial time delay unit is a unit cell of a ground-plane-backed miniaturized-element frequency selective surface (MEFSS) composed of non-resonant elements. Each element is a lowpass type MEFSS composed of a stack of non-resonant patches separated from one another by thin dielectric substrates and the whole structure is backed with a ground plane. A prototype of the proposed MEFSS-based TTD reflectarray with the focal length to aperture diameter ratio (*f/D*) of 0.87 operating at the center frequency of 10 GHz was designed, fabricated, and experimentally characterized both in time and frequency domains. It was demonstrated that the fabricated TTD reflectarray operates over a bandwidth of 40% without any significant chromatic aberrations. The proposed antenna provides a realized gain of 23 dB when fed with an X-band horn antenna and shows a gain variation of about 4 dB in the 8-12 GHz range. The antenna also shows consistent radiation characteristics and relatively low sidelobe levels across its entire band of operation. The results of this investigation are published in the form of a conference paper [C5] and a journal paper on this effort was prepared and submitted to the IEEE Transactions on Antennas and Propagation. This manuscript is currently under review [J13].

6. Physics of Microwave Breakdown in High-Power Microwave Metamaterials and Periodic Structures

6.1. Investigating the Impact of Microwave Breakdown on the Responses of High-Power Microwave Metamaterials

We investigated the effect of microwave-induced breakdown on the frequency responses of a class of metamaterials composed of planar sub-wavelength periodic structures. When breakdown occurs in such a structure, its frequency response changes based on the nature of the plasma created within its unit cell. We examined how the frequency responses of such periodic structures change as a result of creation of microwave-induced discharges within their unit cells. To do this, we examined single-layer metasurfaces composed of miniature LC resonators arranged in a 2-D periodic lattice. These metasurfaces are engineered to be opaque at microwave frequencies when operated at low power levels but can be made transparent if a localized discharge is created within the LC resonators. By measuring their transmission and reflection coefficients under high-power excitation in different conditions, the impact of breakdown on the frequency responses of these devices was determined. Several prototypes of such structures were examined both theoretically and experimentally. It was demonstrated that when breakdown occurs in air and at atmospheric pressure levels, the responses of such periodic structures can be predicted with a reasonable degree of accuracy. Additionally, when the unit cell of the metasurface was composed of two different resonators, breakdown was always observed to occur in both resonators despite their different topologies and local field enhancement factors. In such structures, the discharge in one resonator was found to mediate the discharge in the other resonator. The results of our investigations in this area were published in a number of conference papers [C1], [C2], [C7], [C8], [C13] and a journal paper published in IEEE Transactions on Plasma Science [J14].

6.2. Investigating the Physics of Simultaneous Breakdown Events in High-Power-Microwave (HPM) Metamaterials With Multiresonant Unit Cells and Discrete Nonlinear Responses

Electromagnetic metamaterials offer a significant potential to enable new capabilities in many applications. Under high-power illumination, metamaterials and periodic structures experience internal breakdown, altering frequency response, and/or yielding thermal damage. As part of this project (see Section 6.1), we observed simultaneous breakdown discharges at two separate sites within a multi resonator metamaterial unit cell, even though the electric field intensities at one of the resonator sites should have been well below the threshold intensity required for breakdown. In this part of the project, we investigated three candidate mechanisms for the simultaneous breakdown discharges: energetic electrons, ultraviolet (UV) radiation, and vacuum UV (VUV) radiation. Experiments inserting different dielectric barriers between the two resonators of a multiresonator unit cell were able to selectively isolate the coupling influence of the candidate mechanisms. It was established that, VUV radiation from the discharge at the resonator with a lower electric field breakdown threshold causes simultaneous breakdown at the other resonator where the field intensities are otherwise too low to induce breakdown. The results of this investigation were published in a number of conference papers [C2], [C7] as well as a journal paper published in IEEE Transactions on Plasma Science [J15]. Using this concept and in collaboration with Prof. John H. Booske at the Department of Electrical and Computer Engineering of the University of Wisconsin-Madison, we demonstrated that such single-layer metasurfaces can be used to reduce the threshold breakdown and the breakdown delay in a distributed discharge limiter. The results of this study were published in a number of conference papers [C9], [C10].

7. Metamaterial-Enhanced Traveling Wave Tubes

The growing need for high power sources at millimeter-wave (MMW) frequencies has been motivated by a number of applications ranging from high-data rate communication systems to homeland security and radar applications. Although solid state power amplifiers are relatively good candidates for high power generation in the S and C bands (2-8 GHz), their power gain performance rapidly deteriorates in the MMW range. Vacuum electronics amplifiers such as Traveling Wave Tubes (TWTs) have superior power and efficiency capabilities at MMW and THz regions compared to solid state power amplifiers. However, at these frequencies, the extremely small dimensions of the slow-wave structures (SWS) used in TWTs limits their maximum beam diameter and beam current and consequently their gain and total output power levels. Therefore, at these frequency bands, it is desirable to increase the size of the SWS of a TWT without decreasing the primary frequency band of operation of the SWS. This allows for increasing the beam diameter and total beam current of the TWT resulting in a higher gain and output power level.

As part of this project, we examined this “reverse-miniaturization” concept in a folded waveguide TWT (FWTWT), since they are easier to fabricate at MMW frequencies compared to other types of TWTs such as helix or ring bar TWTs. We demonstrated that when a folded waveguide SWS is loaded with epsilon negative (ENG) metamaterial slabs periodically, its band diagram is shifted to higher frequencies. To reduce the frequency of the main band of the SWS back to the desired (lower) frequency range, we scale the dimensions of the SWS up and obtain a larger structure that has a larger beam tunnel compared to that of the unloaded SWS. Through Particle In Cell (PIC) simulations in CST Studio, we were able to demonstrate that the metamaterial-enhanced TWT has a considerably higher interaction impedance than the unloaded structure and can achieve a larger gain. Additionally, because of the larger beam diameter, the beam current can also be increased further increasing the amplifier’s gain. We were also able to propose practical implementation techniques that may be used to implement the metamaterial loadings in these types of TWTs. These implementations do not use any sort of resonant-elements and use exclusively metallic structures. Therefore, these metamaterial-enhanced traveling wave tubes are not expected to be susceptible to breakdown and they are expected to be capable of handling significantly high CW and pulsed power levels. Using PIC simulations in CST Particle Studio, we were able to demonstrate that these physically realizable metamaterial-enhanced TWTs maintain similar high interaction impedance levels as the ones that use ideal, physically unrealizable metamaterials. The results of our investigations in this area are published in a number of conference papers [C3], [C6]. Additionally, a manuscript of a journal paper in this area is also prepared that will be submitted to IEEE Transactions on Plasma Science.

8. Publications Resulted from This Effort

The list of the papers published as a result of this effort is provided. The list is divided into two sections of journal papers and conference papers. Some of the co-authors of these papers are students that worked on this project and were advised by the PI. These students or advisees are marked with a # sign next to their names in the citations below.

6.1. Journal Papers

J1. Chien-Hao Liu[#] and N. Behdad, "Tunneling and filtering characteristics of cascaded ε-negative metamaterial layers sandwiched by double-positive layers," *Journal of Applied Physics*, Vol. 111, No. 1, pp. 014906 - 014906-9, Jan. 2012.

J2. Chien-Hao Liu[#] and N. Behdad, "Theoretical examination of electromagnetic wave tunneling through cascaded ϵ- and μ-negative metamaterial slabs," *Progress in Electromagnetic Research B*, vol. 42, pp.1-22, 2012.

J3. C.-H. Liu[#] and N. Behdad, "High-power microwave filters and frequency selective surfaces exploiting electromagnetic wave tunneling through epsilon-negative layers," *Journal of Applied Physics*, vol. 113, no. 6, pp. 064909-064909-9 2013. (9 Pages)

J4. M. Li[#] and N. Behdad, "Frequency Selective Surfaces for High Power Microwave (HPM) Applications," *IEEE Trans. Antennas and Propag.*, vol. 61, pp. 677-687, February 2013.

J5. Meng Li[#] and N. Behdad, "A Third Order Bandpass Frequency Selective Surface with a Tunable Transmission Null," *IEEE Transactions on Antennas and Propagation*, Vol. 60, no. 4, pp. 2109-2113, April 2012

J6. Meng Li[#] and N. Behdad, "Fluidically Tunable Frequency Selective/Phase Shifting Surfaces for High Power Microwave Applications," I*EEE Transactions on Antennas and Propagation*, Vol. 60, no. 6, pp. 2748-2759, June 2012.

J7. M. Al-Joumayly[#] and N. Behdad, "Wideband Planar Microwave Lenses Using Sub-Wavelength Spatial Phase Shifters," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 12, pp. 4542-4552, Dec. 2011.

J8. W. Capecchi, N. Behdad, and F. Volpe, "Reverse Chromatic Aberration and its Numerical Optimization in a Metamaterial Lens," *Optics Express*, Vol. 20, no. 8, pp. 8761-8769, 2012.

J9. M. Li[#], M. A. Al-Joumayly, and N. Behdad, "Broadband True-Time-Delay Microwave Lenses Based on Miniaturized-Element Frequency Selective Surfaces," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 3, pp. 1166-1179, March 2013.

J10. M. Li[#] and N. Behdad, "Wideband True-Time-Delay Microwave Lenses Based on Metallo-Dielectric and All-Dielectric Lowpass Frequency Selective Surfaces," *IEEE Transactions on Antennas and Propagation,* vol. 61, no.8, pp. 4109-4119, Aug. 2013.

2014 Winner of the R. W. P. King Prize Paper Award of the IEEE Antennas and Propagation Society.

J11. (Invited Paper) N. Behdad, "A Review of Recent Advances in Designing True-Time-Delay Microwave Lenses Exploiting Metamaterials with Non-Resonant Constituting Unit Cells," *Accepted for Publication in the Applied Computational Electromagnetics Society Journal*, July 2014.

J12. S. M. A. Momeni Hasan Abadi and N. Behdad, "Design of Wideband, FSS-Based Multi-Beam Antennas Using the Effective Medium Approach," *submitted to IEEE Transactions on Antennas and Propagation*, March 2014.

J13. S. M. A. Momeni Hasan Abadi, K. Ghaemi and N. Behdad, "Ultra-Wideband, True-Time-Delay Reflectarray Antennas Using Ground-Plane-Backed, Miniaturized-

Element Frequency Selective Surfaces," *submitted to IEEE Transactions on Antennas and Propagation*, June 2014.

J14. C.-H. Liu# and N. Behdad, "Investigating the Impact of Microwave Breakdown on the Responses of High-Power Microwave Metamaterials," *IEEE Transactions on Plasma Science*, vol. 41, no. 10, part 2, pp. 2992-3000, Oct. 2013.

J15. C.-H. Liu#, J. Neher#, J. H. Booske, and N. Behdad, "Investigating the Physics of Simultaneous Breakdown Events in High-Power-Microwave (HPM) Metamaterials with Multiresonant Unit Cells and Discrete Nonlinear Responses," *IEEE Transactions on Plasma Science*, vol. 42, no. 5, part 1, pp. 1255-1264, May 2014.

6.2. Conference Papers

C1. C. H. Liu# and N. Behdad, "Metamaterials with Discrete Nonlinear Responses for High-Power Microwave Applications," *IEEE Pulsed Power & Plasma Science*, San Francisco, CA 16-21 June 2013. **Invited Paper and Winner of student paper competition.**

C2. C.-H. Liu#, J. Neher#, J. H. Booske, and N. Behdad, "Investigating the Physics of Simultaneous Breakdown Events in Metamaterials with Multi-Resonant Unit Cells," *15th IEEE International Vacuum Electronics Conference,* April 22-24, 2014, Monterey, CA.

C3. A. Rashidi# and N. Behdad, "Metamaterial-Enhanced Traveling Wave Tubes," *15th IEEE International Vacuum Electronics Conference,* April 22-24, 2014, Monterey, CA

C4. S. M. A. Momeni Hasan Abadi# and N. Behdad, "Wideband Multi-Beam Antenna Apertures Using Metamaterial-Based Superstrates," *2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, July 6-12, 2014, Memphis, TN. **Received honorable mention in the student paper competition of the conference.**

C5. S. M. A. Momeni Hasan Abadi# and N. Behdad, "Ultra-Wideband, True-Time-Delay, Metamaterial-Based Reflectarray Antenna," *2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, July 6-12, 2014, Memphis, TN.

C6. A. Rashidi# and N. Behdad, "Metamaterial-Enhanced Slow-Wave Structures for Traveling Wave Tube Applications," *2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, July 6-12, 2014, Memphis, TN.

C7. C.-H. Liu# and N. Behdad, "Investigating Failure Mechanisms in High-Power Microwave Frequency Selective Surfaces," *Submitted to the 2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, July 6-12, 2014, Memphis, TN. **Received honorable mention in the student paper competition of the conference.**

C8. C.-H. Liu#, J. Neher#, J. H. Booske, and N. Behdad, "Investigating the Physics of Microwave Induced Breakdown in Metamaterials with Multi-Resonant Constituting Unit

Cells," *55th Annual Meeting of the APS Division of Plasma Physics,* Vol. 58, no. 16, November 11-15 2013, Denver, CO.

C9. J. H. Booske, B. Kupczyk, A. Garcia, C.-H. Liu#, X. Xiang, N. Behdad, and J. Scharer, "Reduced breakdown delay in high power microwave dielectric window discharges via penning-like mixtures and patterened metallization," *55th Annual Meeting of the APS Division of Plasma Physics,* Vol. 58, no. 16, November 11-15 2013, Denver, CO.

C10. B. Kupczyk, C. H. Liu#, X. Xiang, N. Behdad, J. Scharer, and J. H. Booske, "Reduced Breakdown Delay in High Power Microwave Dielectric Window Discharges," *IEEE Pulsed Power & Plasma Science*, San Francisco, CA 16-21 June 2013.

C11. S. M. A. Momeni Hasan Abadi# and N. Behdad, "Multi-Beam Antennas Using Planar Lenses Fed With Focal Plane Arrays," *2013 AP-S/URSI Symposium*, Orlando, FL.

C12. M. Li# and N. Behdad, "All-Dielectric, True-Time-Delay, Planar Microwave Lenses," *2013 AP-S/URSI Symposium*, Orlando, FL. **Finalist in the student paper competition. One of the 15 finalists selected from among ~150 submissions worldwide.**

C13. C.-H. Liu# and N. Behdad, "Plasma tunable metamaterials and periodic structures," *2013 International Vacuum Electronics Conference (IVEC 2013)*, pp. 1-2, DOI: 10.1109/IVEC.2013.6571008.

C14. Chien-Hao Liu# and N. Behdad, "Analysis of Electromagnetic Wave Tunneling Through Stacked Single-Negative Metamaterial Slabs: a Microwave Filter Theory Approach," *2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*, July 8-14, 2012, Chicago, IL, pp. 1-2 (DOI: 10.1109/APS.2012.6349305).

C15. Chien-Hao Liu# and N. Behdad, "High-Power Microwave Filters and Frequency Selective Surfaces Utilizing EM Wave Tunneling Through ε-Negative Layers," *2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*, July 8-14, 2012, Chicago, IL, pp. 1-2 (DOI: 10.1109/APS.2012.6349304). **Finalist in the student paper competition. One of the 15 finalists selected from among ~150 submissions worldwide.**

C16. M. Li# and N. Behdad, "Frequency Selective Surfaces for High-Power Microwave (HPM) Applications," *2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*, July 8-14, 2012, Chicago, IL, pp. 1-2 (10.1109/APS.2012.6348722).

C17. M. Li# and N. Behdad, "Ultra-Wideband, True-Time-Delay, Metamaterial-Based Microwave Lenses," *2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting*, July 8-14, 2012, Chicago, IL, pp. 1-2 (DOI: 10.1109/APS.2012.6349044).

C18. Chien-Hao Liu# and N. Behdad, "Electromagnetic Wave Tunneling Through Multiple Epsilon-Negative Metamaterial Layers: A Microwave Filter Theory Approach," *USNC/URSI National Radio Science Meeting*, January 4-7, 2012 Boulder, CO.

C19. M. Li# and N. Behdad, "Fludically Tunable Phase Shifting Surfaces for High-Power Tunable Lens Applications," *2011 Antenna Applications Symposium,* Robert

Allerton Park, Monticello IL, September 20-22, 2011. **Winner of the second place award in the student paper competition.**

C20. M. Al-Joumayly# and N. Behdad, "Wideband True-Time-Delay Microwave Lenses Using Low-Profile, Sub-wavelength Periodic Structures," *IEEE Int. Symp. Antennas and Propag. & USNC/URSI Nat. Radio Sci. Meeting*, July 3-8, 2011, Spokane WA.

C21. M. Al-Joumayly# and N. Behdad, "High-Resolution Discrete Lens Arrays Using Miniaturized-Element Frequency Selective Surfaces," *IEEE Int. Symp. Antennas and Propag. & USNC/URSI Nat. Radio Sci. Meeting*, July 3-8, 2011, Spokane WA.

9. Inventions and Patents Resulted from This Effort

1. "True-Time-Delay, Low-Pass Lens," Inventors: N. Behdad and Meng Li, Utility patent application filed with U.S. Patent and Trademark Office (U. S. App. No. 13/483,381) filed on 5/30/2012.
2. Epsilon-negative Loaded Traveling Wave Tube, Inventors: Arash Rashidi and Nader Behdad, filed with USPTO on 3/10/2014 (USSN 14/202,992).

10. Awards and Recognitions that Resulted From This Effort

1) **The 2014 R. W. P. King Prize Paper Award of the IEEE Antennas and Propagation Society** *for the paper:*
   - M. Li and N. Behdad, "Wideband True-Time-Delay Microwave Lenses Based on Metallo-Dielectric and All-Dielectric Lowpass Frequency Selective Surfaces," IEEE Transactions on Antennas and Propagation, vol.61, no.8, pp.4109-4119, August 2013.

2) **Winner of the Student Paper Competition of the 2014 IEEE Pulsed Power & Plasma Science Conference** *for the paper:*
   - C. H. Liu and N. Behdad, "Metamaterials with Discrete Nonlinear Responses for High-Power Microwave Applications," *IEEE Pulsed Power & Plasma Science*, San Francisco, CA 16-21 June 2013.

3) **Second Place in the Student Paper Competition of the 2011 Antenna Applications Symposium** *for the paper:*
   - M. Li# and N. Behdad, "Fludically Tunable Phase Shifting Surfaces for High-Power Tunable Lens Applications," *2011 Antenna Applications Symposium,* Robert Allerton Park, Monticello IL, September 20-22, 2011.

4) **One of the 15 finalist (from ~150 submissions worldwide) in the student paper competition of the 2012 IEEE Antennas and Propagation Society Internal Symposium** *for the paper:*
   - Chien-Hao Liu# and N. Behdad, "High-Power Microwave Filters and Frequency Selective Surfaces Utilizing EM Wave Tunneling Through ε-Negative Layers,"

2012 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, July 8-14, 2012, Chicago, IL, pp. 1-2.

5) **One of the 15 finalist (from ~150 submissions worldwide) in the student paper competition of the 2013 IEEE Antennas and Propagation Society Internal Symposium** *for the paper:*
    - M. Li# and N. Behdad, "All-Dielectric, True-Time-Delay, Planar Microwave Lenses," *2013 AP-S/URSI Symposium*, Orlando, FL.

6) **Honorable mention in the student paper competition of the 2014 IEEE Antennas and Propagation Society Internal Symposium** *for the paper:*
    - C.-H. Liu# and N. Behdad, "Investigating Failure Mechanisms in High-Power Microwave Frequency Selective Surfaces," *Submitted to the 2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, July 6-12, 2014, Memphis, TN

7) **Honorable mention in the student paper competition of the 2014 IEEE Antennas and Propagation Society Internal Symposium** *for the paper:*
    - S. M. A. Momeni Hasan Abadi# and N. Behdad, "Wideband Multi-Beam Antenna Apertures Using Metamaterial-Based Superstrates," *2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, July 6-12, 2014, Memphis, TN